

## **3S<sup>2</sup>: Behavioral Response studies of Cetaceans to Navy Sonar Signals in Norwegian Waters**

Peter L. Tyack  
University of St Andrews  
School of Biology  
Scottish Oceans Institute  
East Sands  
St Andrews, Fife, KY16 8LB  
United Kingdom  
phone: +44 (0) 1334 462630 email: [plt@st-andrews.ac.uk](mailto:plt@st-andrews.ac.uk)

Award Number: N000140810661  
<http://www.smru.st-and.ac.uk>

### **LONG-TERM GOALS**

A primary goal of this international cooperative research program was to investigate behavioral reactions of three species of whales (bottlenose whales, minke whales, and humpback whales) elicited by exposures to quantified dosages of naval active sonar signals in the 1-2 kHz range. The results are analyzed to establish dose:response functions for sonar operations for these species. Another primary goal of the program was to assess the effectiveness of “ramp-up,” a common mitigation protocol in which source levels are gradually increased prior to the onset of full-level transmissions. Ramp-up is designed to give nearby animals the chance to move away before sonar transmissions reach maximum levels. However, it is unknown whether or not this protocol is actually effective for animals in their natural environment. We developed and implemented an experimental design to test whether the ‘ramp-up’ procedure is an effective protocol to reduce risk of harm from sonar activities. This is the final report of this project.

### **OBJECTIVES**

In this research project, our specific objectives are to: 1.) Expand the 3S comparative experimental dataset to include species that are potentially more sensitive even if they are difficult to study: Northern bottlenose whale (*Hyperoodon ampullatus*, family Ziphiidae) and minke whale (*Balaenoptera acutorostrata*, family Balaenopteridae). The goal is to identify behavioral response thresholds during exposure experiments, and to compare these to responses to no-sonar controls and playback of killer whale sounds; 2.) Conduct a directed study on the effectiveness of ramp-up as a mitigation method with abundant and relatively easy-to-study humpback whales (*Megaptera novaeangliae*, family Balaenopteridae); 3.) Record sufficient no-sonar baseline data of all target species to statistically compare experimental records with baseline records and to adequately describe the behavioral significance of recorded changes in behavior; and 4.) Develop collaborations between the 3S research group with the MOCHA project and other research groups undertaking similar projects to pool data where appropriate, share expertise and reduce overall project costs.

## APPROACH

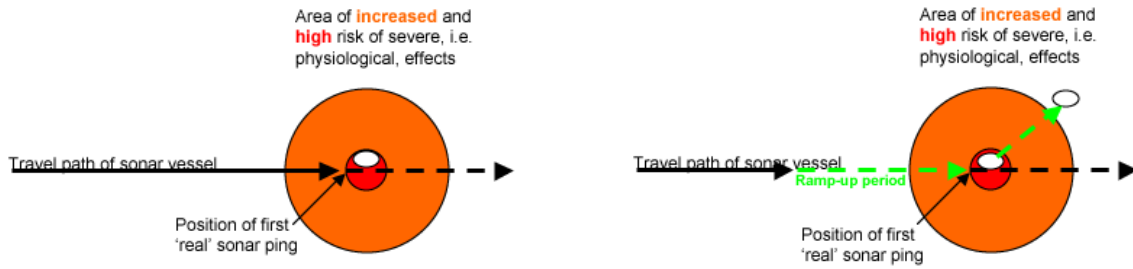
### *Objective 1*

The earlier 3S dataset (see related programs) with killer, sperm, and long-finned pilot whales (Miller et al., 2012) as well as the 3S<sup>2</sup> experiments with humpback whales enabled comparative analysis of behavioral response sensitivities. The goal here was to expand the 3S comparative dataset of behavioral response experiments to include species that are potentially more sensitive and difficult to study: Northern bottlenose whale (*Hyperoodon ampullatus*, family Ziphiidae) and minke whale (*Balaenoptera acutorostrata*, family Balaenopteridae). Sonar-related strandings have commonly involved Ziphiids in temperate or tropical waters, but in the North Atlantic have also included the Northern bottlenose whale (Canary Islands), and the minke whale (Bahamas). It is unclear whether the low numbers of Northern bottlenose whales and minke whales documented in sonar-related stranding events result from lower sensitivity to sonar or because they are present in lower numbers in the areas where stranding events have been documented. Directed research on the behavioral responses of these two species is needed to resolve this question (Tyack et al., 2004). The goal was to identify behavioral response thresholds during controlled exposure experiments, and to compare these to responses to no-sonar negative controls and positive controls consisting of playback of killer whale sounds.

The 3S<sup>2</sup> field experiments followed similar dose-escalation protocols, in which the level received by the whale subject is increased in order to identify the acoustic threshold for any observed response. Movements of the sonar source vessel and source-level ramp up protocols were specific to each species. For northern bottlenose whales, the protocol was for the source vessel to move slowly along a predetermined box near the tagged whale, with a long (20-min) rampup of source levels from 153-214 dB re 1μPa @ 1m to achieve received level dose escalation (Miller et al., 2015). This relatively fixed source position was designed specifically to more closely match experimental protocols used with beaked whales in the AUTECH (Tyack et al., 2011) and SOCAL studies (DeRuiter et al., 2013; Stimpert et al., 2014). Minke whale exposures started sonar exposure sessions at ~8km distance with a 10-minute ramp up of source levels from 152-214 dB re 1μPa @ 1m. The tagged minke whale was approached at 4.4m/s to further increase received levels, and transmissions stopped after a maximum of 1hr exposure duration (Sivle et al., in press).

### *Objective 2*

Study the effectiveness of ramp-up as a mitigation method with abundant and relatively easy-to-study humpback whales (*Megaptera novaeangliae*, family Balaenopteridae). Animals close to the location of the first full-level sonar transmission are at the greatest risk of severe effects such hearing effects including temporary or permanent threshold shift (left panel of Fig. 1). Ramp-up transmissions prior to full-level transmissions could be effective if animals move far enough away from the immediate location of the full-level sonar pings to avoid hearing damage (right panel of Fig. 1). Thus, the ramp-up protocol is itself based upon the principle of behavioral response – in this case an avoidance response to the ramp-up transmissions that protects the animals from receiving intense sound levels. The 5-minute rampup protocol of 0.5s duration pulses from 152 to 214 dB re 1μPa @ 1m used in this study was based upon a simulation-based theoretical analysis of the effectiveness of ramp-up (von Benda-Beckmann et al., 2013).



**Figure 1. A conceptual diagram of the role of ramp-up before full-level sonar operations. Left: Animals near the position of the first full-power sonar transmissions are at a higher risk of severe effects. Right: The ramp-up procedure implies that sonar sounds are started earlier, at lower levels, and are gradually increased to full power at the planned position. These additional ramp-up transmissions are designed to give animals within the zone of increased risk time to move away.**

To experimentally test the effectiveness of ramp-up, we conducted three kinds of sonar exposure with each tagged humpback whale: a no sonar-control session, ramp-up exposure session 1, and rampup exposure session 2. All sessions used the same approach protocol, starting 1.3km from the tagged whale, with the vessel moving at 4m/s towards the tagged whale with no turns after the start of sonar transmissions. The 5-minute rampup period was designed to be completed just as the source boat reached the point of closest approach to the whale after which 5 minutes of full-level transmissions were made. After creating high-resolution 3D tracks of whale positions (Wensveen et al., 2015), we quantified the maximum sound pressure level ( $SPL_{max}$ ) and cumulative sound exposure level ( $SEL_{cum}$ ) received by the whale using a Bellhop sound-propagation model. For real sonar exposures, modelled received levels were compared to measured values. Received level values for the no-rampup condition were modelled from the no-sonar control sessions, based upon the assumption that whale responses to the sonar could not influence received levels of full level transmissions that started near the whale with the source vessel then moving away from the whale. Two actual no-rampup sessions were conducted in 2012. Modelled received levels during ramp-up sessions were compared with RLs during no-rampup sessions, and were statistically explored accounting for session type, session order, Attraction (y/n), avoidance (y/n), Avoidance Order, and Feeding (y/n) prior to exposure (see Wensveen et al. submitted for details).

### *Objective 3*

Record sufficient no-sonar baseline data from all target species to test whether recorded changes in behavior were likely responses to sonar, to adequately describe the behavioral significance of recorded changes in behavior, and to statistically compare experimental records with baseline records. No-sonar baseline data were obtained from pre-exposure periods of tag records prior to sonar exposure sessions and from tag deployments with no sonar exposures.

### *Objective 4*

Develop collaborations between the 3S research group with the MOCHA project and other research groups undertaking similar projects to pool data where appropriate, share expertise and reduce overall project costs.

## WORK COMPLETED

All of the four objectives of the 3S<sup>2</sup> project were successfully addressed during this project. The 3S<sup>2</sup> experimental dataset includes a total of 11 humpback whale sonar experiments during which one or more whales were tagged with version 2 Dtags plus Sirtrac GPS loggers. These humpback whales were subjects in 11 no-sonar control sessions, 20 1-2 kHz upsweep exposure sessions, and 8 killer whale sound playbacks with separate noise control playbacks (Table I). One minke whale was tagged in 2011 using a dive logger tag (Ctag), during which one no-sonar control and one 1-2kHz upsweep sonar exposure session was conducted. For the northern bottlenose whale, we conducted one experiment in 2013 with a whale tagged with a version 2 Dtag, during which one 1-2 kHz upsweep sonar exposure was conducted.

*Table I. Summary of sonar experiment data-/set collected by the 3S-BRS study. Data collected by the 3S<sup>2</sup> research project (N00014-10-1-0355) are within blue cells.*

| Species           | # TAGs deployed | # Sonar sessions | # Control sessions | Trials/year                        |
|-------------------|-----------------|------------------|--------------------|------------------------------------|
| Killer whales     | 22              | 8                | 3                  | 3S-05, 3S-06, 3S-08, 3S-09, ICE-09 |
| Pilot whales      | 34              | 14               | 28                 | 3S-08, 3S-09, 3S-10, 3S-13         |
| Sperm whales      | 10              | 10               | 9                  | 3S-08, 3S-09, 3S-10                |
| Herring           | 0               | 38               | 25                 | 3S-06, 3S-08                       |
| Minke whales      | 2               | 1                | 2                  | 3S-10, 3S-11                       |
| Bottlenose whales | 6               | 1                | 0                  | 3S-13, JM-14 (co-funded by SERDP)  |
| Humpback whales   | 27              | 20               | 29                 | 3S-11, 3S-12                       |
| SUM               | 106             | 93               | 98                 |                                    |

## RESULTS

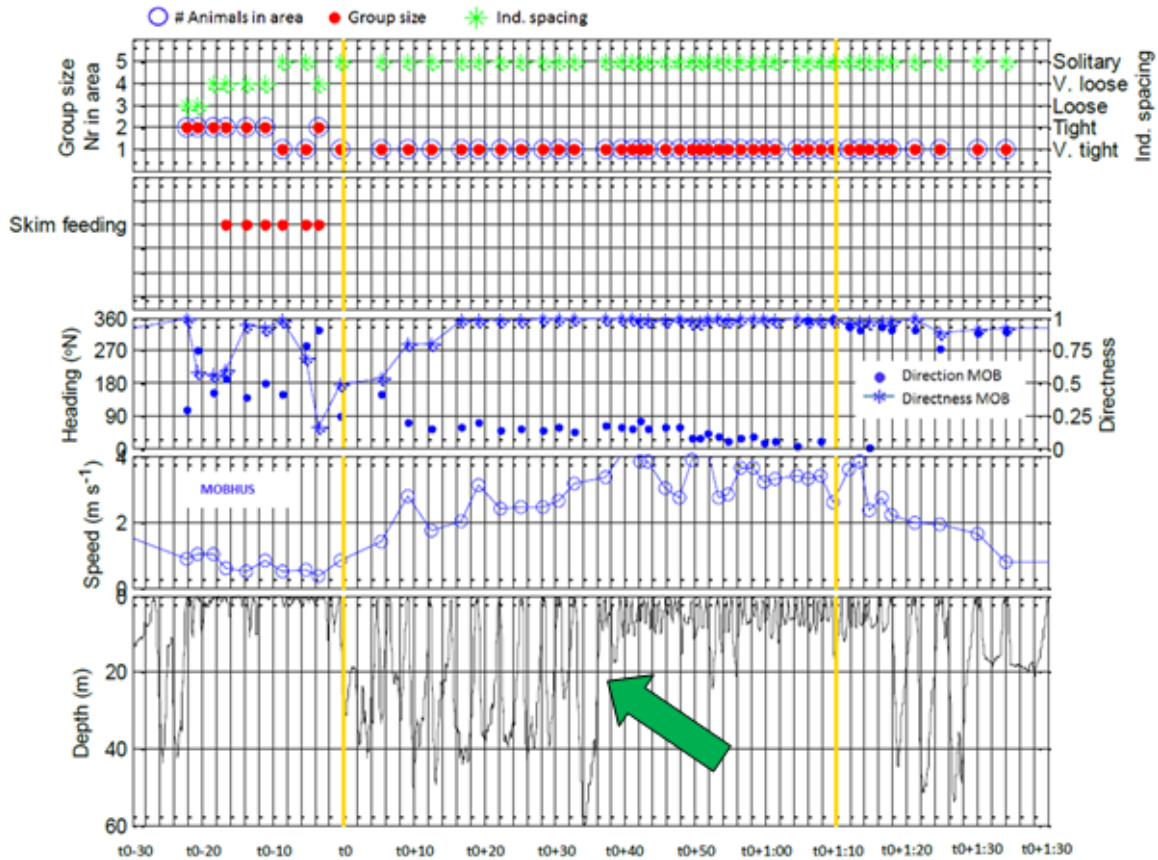
Objective 1: response of cetaceans to sonar. In this study, we obtained important new data on how northern bottlenose, minke, and humpback whales respond to 1-2 kHz sonar signals. Minke and northern bottlenose whales proved to be more difficult to tag than humpback whales, and despite intensive efforts over all three field efforts, only a single sonar experiment was achieved for those two species (Table I). All of these data have been qualitatively inspected using severity scoring (Southall et al., 2007) of expert-identified responses (Sivle et al., in press), and have also been analyzed quantitatively (Miller et al., 2015; Curé et al., 2015; Kvadsheim et al., in prep; Wensveen et al., submitted).

**Table II. Number of exposure sessions ranked by maximum response severity score and sorted by exposure and stimulus type. Numbers in [brackets] are bottlenose whale data, numbers in (parenthesis) are minke whale data, and humpback whale data otherwise. The total number of responses includes all scored behavioral responses, not just the response with the maximum score. From Sivle et al. (in press).**

| Severity                     | No-sonar control | Sonar1    | Sonar2    | Killer whale PB | Noise PB |
|------------------------------|------------------|-----------|-----------|-----------------|----------|
| 9                            |                  |           |           |                 |          |
| 8                            |                  | (1)[1]    |           |                 |          |
| 7                            |                  | 1         |           | 4               |          |
| 6                            | 1                | 3         | 2         | 2               | 1        |
| 5                            |                  | 1         | 1         | 1               | 1        |
| 4                            | 1                | 2         | 1         |                 | 1        |
| 3                            | 2                |           | 2         |                 |          |
| 2                            | (1)              | 2         | 1         | 1               |          |
| 1                            |                  |           |           |                 |          |
| 0                            | 8                | 2         | 3         |                 | 5        |
| Total # of exposure sessions | <b>13</b>        | <b>13</b> | <b>10</b> | <b>8</b>        | <b>8</b> |
| Total # responses            | <b>7</b>         | <b>24</b> | <b>9</b>  | <b>18</b>       | <b>9</b> |

Overall, the severity scoring of expert-identified responses indicated that responses to the sonar were more numerous and of higher severity than responses to no-sonar control experiments, indicating that responses were driven by the sonar transmissions and not the source vessel movements (Table I). For humpback whales, responses were most consistent and severe to killer whale playback (Curé et al., 2015), demonstrating that biologically-relevant playbacks are useful as a positive experimental control stimulus. More responses of higher severity were apparent in the first sonar session (Sonar1) than the second session (Sonar2), indicating possible habituation to the sonar transmissions between those two sessions (Sivle et al., in press).

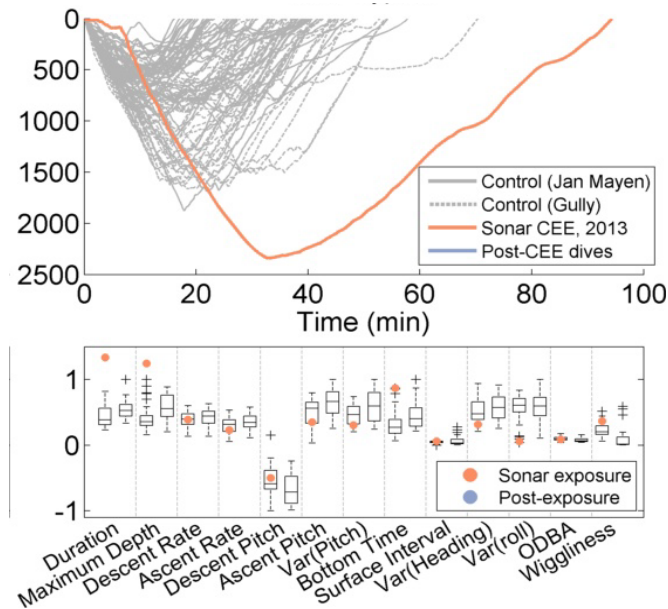
Though it was only possible to conduct one sonar exposure experiment each for minke and northern bottlenose whales, level 8 severity behavioral responses were identified for both species (Table II) indicating they were more sensitive to sonar than humpback whales. The tagged minke whale responded to sonar exposure by cessation of skim-feeding and strong avoidance which escalated to an even higher speed associated with clear changes in the dive profile throughout the exposure session (Fig. 1). In contrast, little change was observed during the no-sonar vessel approach. Statistical analysis of the minke whale time series also indicates a break-point in the movement time-series. The statistical results are currently being combined for publication together with results from a single minke whale experiment carried out by the SOCAL BRS team (Kvadsheim et al., in prep).



**Figure 1. Time-series data of the 1-2 kHz sonar exposure with a tagged minke whale. Data in the top 4 panels were derived from observations from the trackboat ('MOB'). Note the strong change in diving behavior at the start of the exposure which was associated with increasing speed and a straight heading as the whale moved away from the source. The green arrow marks the time when progressive aversion was apparent, which was the most severe (severity 8) behavioral response identified. From Sivle et al., (in press).**

A strong behavioral response to sonar was also indicated in the single experiment with northern bottlenose whales (Miller et al., 2015; Sivle et al., in press). Based upon cessation of clicking and directed movement away from the sonar source, severity scoring identified prolonged cessation of feeding (severity 7) and long-term avoidance of the area (severity 8). Though a no-sonar control session was not conducted, the sonar exposure started at a range of 4-5km and the source vessel moved in a pre-determined box (Miller et al., 2015), so there is less concern that source vessel movement rather than sonar transmissions drove the responses observed in that experiment. The silent deep dive performed by this whale (Fig. 2, top panel) was highly unusual both for being the longest-duration and deepest of 79 deep-dives recorded for the species. The fact that no foraging-related sounds were produced during the dive was very unusual, as echolocation-based foraging is typically observed during such dives (see Fig. 4 in Miller et al., 2015). The response of the tagged northern bottlenose whale continued until the tag detached from the whale after recording 7-hr of post-exposure data (Fig. 1 in Miller et al., 2015). In the area of the sonar experiments, many fewer whales were detected visually and acoustically in the 6 hr following sonar exposure (Fig 5 in Miller et al., 2015). These observations indicate that those whales may have shown similar avoidance behavior as the tagged

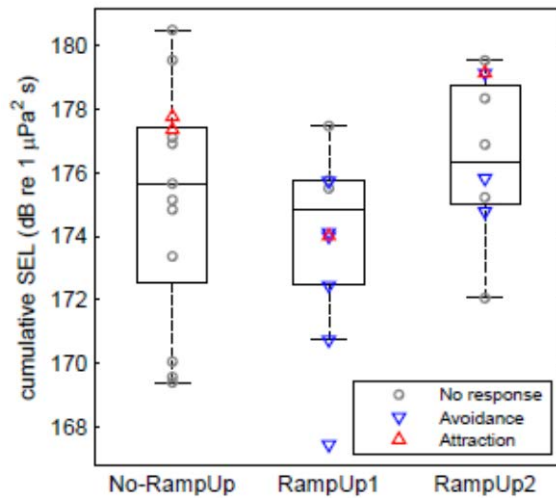
whale. In future work with such apparently sensitive species, we recommend that (in addition to highly detailed measurements possible with short-term suction cup tags) the full spatial and temporal nature of responses to noise exposure be measured using longer-duration observation tools such as ARGOS-linked SPLASH tags (Shorr et al., 2014) and bottom-mounted acoustic buoys (Moretti et al., 2015).



**Figure 2. Dive profiles (top) and statistical distribution of dive parameters (bottom) of 79 long-deep dives of northern bottlenose whales. Baseline data were collected near Jan Mayen, Norway and in the Gully, Canada. Note the clearly unusual depth and duration of the sonar-response dive, including its unusual initial descent pattern. From Miller et al. (2015).**

Objective 2: effectiveness of the ramp-up procedure. As described above, 11 experiments following the ramp-up study design were successfully conducted with humpback whales. To estimate the received levels received by whales in ‘no-rampup’ versus ‘rampup’ conditions, it was necessary to reconstruct the whale track at a 20s resolution to fix each whale’s position at the time of each sonar transmission. This was accomplished using a novel track reconstruction method that combines the depth and orientation information provided by Dtags with location information provided by visual fixes and GPS loggers attached to the Dtags, while accounting for errors in sensor capability (Wensveen et al., 2015). The study demonstrated that using GPS loggers provides a more accurate track than would have been possible using visual sighting locations alone (see Fig 4 in Wensveen et al., 2015), and generated a generically useful track-reconstruction method for the field.

Based upon the reconstructed high-resolution tracks, received levels of sonar (maximum SPL and cumulative SEL) during rampup and no-rampup conditions were compared. Overall, acoustic levels received by whales tended to be slightly lower when full-level transmissions were preceded by the 5-minute ramp-up period (Fig. 3), although the overall difference was not statistically significant. However, the behavioral response of the humpbacks whales to sonar was highly variable (see Table II, above). Statistically-significantly lower received levels (-6dB for  $SPL_{max}$  and -4dB for  $SEL_{cum}$ ) were received by whales that avoided the sound source during the ramp-up period, while higher levels were received by animals that were attracted to the source (Fig. 3).



**Figure 3. Cumulative sound exposure level ( $SEL_{cum}$ ) received by humpback whales in no-rampup versus rampup sessions. Data points are colored by behavioral response category, with blue and red triangles indicating sessions in which avoidance or attraction, respectively, occurred during the ramp-up period. Note that received levels were lower when humpbacks avoided the sonar source during the rampup period. No avoidance was noted during the approach phase of no-rampup sessions, indicating the whales did not avoid the approaching vessel.**

The results indicate that rampup has the potential to reduce sound exposure and thereby lower the risk of physiological damage in humpback whales, but is only effective for individuals that have sufficiently strong avoidance responses during the ramp-up period. A pair of animals composed of a mother with a particularly small calf pair showed strong avoidance during both ramp-up exposure sessions, for example, while other individuals approached the source during the ramp-up period (Fig. 3). Such inter-species variability in avoidance and attraction responses is important to consider when evaluating the potential benefits of a rampup procedure to reduce received levels. Ramp-up is not likely to be effective in reducing received level if animals have strong motivations to stay in their current location. Our study confirms, however, that the rampup procedure can be effective at reducing received sound levels in behaviorally sensitive individuals, and its effectiveness needs to be considered on a case-by-case basis.

**Objective 3: Collection and use of baseline data.** Baseline data were collected as pre-sonar exposure datasets for all 13 tagged humpback whales. These data were successfully used to develop the track-reconstruction method (Wensveen et al., 2015) which was crucial for the test of effectiveness of the rampup procedure. We collected an 8-hr pre-exposure dataset for the minke whales experiment, which has been useful in statistical analysis of its movements (Kvadsheim et al., in prep), though little additional baseline data was collected for the extremely difficult-to-tag minke whale. For bottlenose whales, an 8-hr pre-exposure dataset was successfully recorded for the experiment whale ha13\_176a, which was used to quantify when its behavior during the exposure period deviated from baseline (see Fig. 1 in Miller et al., 2015). In addition, 3S<sup>2</sup> collaborated with a 2014 field project funded the US Strategic Environmental Research and Development Program (SERDP) in which five additional baseline records were obtained for the northern bottlenose whale. Those baseline data were used effectively to statistically evaluate the response of the single northern bottlenose whale that was experimentally exposed to sonar, and to show the highly unusual nature of its behavior when it responded to sonar (Fig. 2, above).

Objective 4: Develop collaborations between 3S and other BRS project groups via the MOCHA project. These collaborations were accomplished by active 3S participation in the Steering Committee (by PIs Miller and Tyack) and Working Group (by 3S collaborators Petter Kvadsheim of FFI, Norway and Frans-Peter Lam of TNO, The Netherlands). Close interaction with MOCHA has led to substantial statistical support for the 3S project, including new methods to quantify dose-response relationships from severity scored of expert-identified behavioral responses (Harris et al., 2015), harmonization of methods to quantify beaked whale response to sonar across 3S and other studies (Miller et al., 2015), and further refinement of statistical approaches to reconstruct animal tracks (Wensveen et al., 2015). 3S is continuing to work with the SOCAL-BRS team on a paper reporting their joint results of sonar exposure experiments with minke whales.

In conclusion, the 3S<sup>2</sup> study has successfully studied the effects of sonar on cetaceans using an experimental approach, and has effectively addressed all of its objectives. Results of the 3S research efforts under this program have been presented at the 2013 Biennial meeting of the Society for Marine Mammalogy in Dunedin, New Zealand, at the 2014 Bio-logging symposium in Strasbourg, France, and the 2014 ESOMM meeting in Amsterdam. A large number of papers have been published in (or submitted to) peer review journals (see Publication list). In addition, 18 Masters or PhD theses have made use of 3S data.

The 3S research was carried out by an international collaborative team from the Sea Mammal Research Unit (SMRU), Woods Hole Oceanographic Institution (WHOI), Norwegian Defense Research Establishment (FFI), and Netherlands Organization for Applied Scientific Research (TNO). WHOI provided v2 Dtags. Project management and logistic support, including acquisition of research vessels and permitting were managed through FFI, led by Dr. Petter Kvadsheim. FFI also provided biological and tagging expertise in collaboration with Lars Kleivane of LKArts. TNO contributed an advanced towed array system for recording and detecting marine mammal sounds (Delphinus), the multi-purpose towed source (Socrates), and staffing during the cruises under the leadership of Frans-Peter Lam, with collaboration from René Dekeling of the Royal Netherlands Navy.

## RELATED PROJECTS

This study is a second phase of the project “Cetaceans and naval sonar: behavioral response as a function of sonar frequency” award number N00014-08-1-0984, which expired in 2011. Additional research focusing on the biological relevance of behavior associated with 3S experiments is conducted under award number N00014-14-1-0390. Method development for future work with *Hyperoodon* is conducted under award N00014-15-1-2533. Statistical support and collaboration is ongoing with the MOCHA project award N00014-12-1-0204. Collaborative research is pursued with Kelp Marine PI Fleur Visser under award N00014-11-1-0298.

## REFERENCES

- von Benda-Beckmann, A.M., P.J. Wensveen, P.H. Kvadsheim, F.P.A. Lam, P.J.O. Miller, P.L. Tyack, M.A. Ainslie (2014). Modelling effectiveness of gradual increases in source level to mitigate effects of sonar on marine mammals. *Cons. Biol* 28: 119-128. (DOI: 10.1111/cobi.12162)
- Curé, C., Sivle, L. D., Visser, F., Wensveen, P. J., Isojunno, S., Harris, C., Kvadsheim, P. H., Lam, F. P. A., Miller, P. J. O. 2015. Predator sound playbacks reveal strong avoidance responses in a fight strategist baleen whale. *Marine Ecology Progress Series*, 526:267-282.

- DeRuiter SL, Southall BL, Calambokidis J, et al. (2013) First direct measurements of behaviour responses by Cuvier's beaked whales to mid-frequency active sonar. *Biology Letters* 9, doi: 10.1098/rsbl.2013.0223
- Harris, C.M., D. Sadykova, S.L. DeRuiter, P.L. Tyack, P.J.O. Miller, P.H. Kvadsheim, F.P.A. Lam, and L. Thomas. (*in press*). Dose response severity functions for acoustic disturbance in cetaceans using recurrent event survival analysis. *Ecosphere*
- Kvadsheim, P. H. et al. in prep. Behavioural responses of minke whales (*Balenoptera acutorostrata*) exposed to sonar. Manuscript in prep.,
- Miller P. J. O., Kvadsheim, P. H., Lam, F. P. A., Tyack, P.L., Curé, C., DeRuiter, S. L., Kleivane, L., Sivle, D. L., van IJsselmuiden, S. P., Visser, F., Wensveen, P. J., von Benda-Beckmann, A. M., Martín López, L. M., Narazaki, T., Hooker, S. K. (2015). First indications that northern bottlenose whales are sensitive to behavioural disturbance from anthropogenic noise. *R. Soc. open sci.* 2: 140484. <http://dx.doi.org/10.1098/rsos.140484>
- Miller, P.J.O., Kvadsheim, P.H., Lam, F.P.A., Wensveen, P.J., Antunes, R., Alves, A.C., Visser, F., Kleivane, L., Tyack, P.L., Sivle, L.D. (2012). The severity of behavioral changes observed during experimental exposures of killer (*Orcinus orca*), long-finned pilot (*Globicephala melas*), and sperm whales (*Physeter macrocephalus*) to naval sonar. *Aquatic Mammals* **38**: 362-401.
- Moretti, D., Thomas, L., Marques, T., Harwood, J., Dilley, A., Neales, B., Shaffer, J., McCarthy, E., New, L., Jarvis, S., *et al.* 2014 A risk function for behavioral disruption of Blainville's beaked whales (*Mesoplodon densirostris*) from mid-frequency active sonar. *PLoS One*. **9**, e85064. (10.1371/journal.pone.0085064)
- Schorr GS, Falcone EA, Moretti DJ, Andrews RD (2014) First long-term behavioral records from Cuvier's beaked whales (*Ziphius cavirostris*) reveal record-breaking dives. *PLoS ONE* 9(3): e92633. doi:10.1371/journal.pone.0092633
- Sivle, L. D., Kvadsheim, P. H., Curé, C., Isojunno, S., Wensveen, P. J., Lam, F. P. A., Visser, F., Kleivane, L., Tyack, P. L., Harris, C. M., Miller, P. J. O. in press. Severity of expert-identified behavioural responses of humpback whale, minke whale, and northern bottlenose whale to naval sonar. *Aquatic Mammals*, in press.
- Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R., . . . Tyack, P. (2007). Marine mammal noise exposure criteria: Initial scientific recommendations. *Aquatic Mammals*, 33(4), 411-521.
- Stimpert, A. K., DeRuiter, S. L., Southall, B. L., Moretti, D. J., Falcone, E. A., Goldbogen, J. A., Friedlaender, A., Schorr, G. S., Calambokidis, J. 2014 Acoustic and foraging behavior of a Baird's beaked whale, *Berardius bairdii*, exposed to simulated sonar. *Sci. Rep.* **4**, 7031. (10.1038/srep07031)
- Tyack PL, Gordon J, Thompson D. 2004. Controlled exposure experiments to determine the effects of noise on marine mammals. *Marine Technology Society Journal* **37**, 41-53.
- Tyack PL, Zimmer WMX, Moretti D, Southall BL, Claridge DE, Durban JW, Clark CW, D'Amico A, DiMarzio N, Jarvis S, McCarthy E, Morrissey R, Ward J, Boyd I. 2011. Beaked whales respond to simulated and actual navy sonar. *PLOS One* 6(3):e17009
- Wensveen, P. J., Kvadsheim, P. H., Lam, F. P. A., von Benda-Beckmann, A. M., Sivle, L. D., Visser, F., Curé, C., Tyack, P. L. and Miller, P. J. O. submitted. The effectiveness of ramp-up of naval

sonar to reduce sound levels received by marine mammals: experimental tests with humpback whales. Submitted to Proc. Roy. Soc. B.

Wensveen, P. J., Thomas, L., Miller, P. J. O. 2015. A patch reconstruction method integrating dead-reckoning and position fixes applied to humpback whales. *Movement Ecology* 3:31. DOI 10.1186/s40462-015-0061-6.

## PUBLICATIONS

Published or submitted peer review articles from the 3S BRS study in chronological order.

Publications marked with a \* indicate core-deliverable papers on the effects of sonar on cetaceans.

\*Wensveen, P. J., Kvadsheim, P. H., Lam, F. P. A., von Benda-Beckmann, A. M., Sivle, L. D., Visser, F., Curé, C., Tyack, P. L. and Miller, P. J. O. submitted. The effectiveness of ramp-up of naval sonar to reduce sound levels received by marine mammals: experimental tests with humpback whales. Submitted to Proc. Roy. Soc. B.

Wensveen, P. J., Thomas, L., Miller, P. J. O. 2015. A path reconstruction method integrating dead-reckoning and position fixes applied to humpback whales. *Movement Ecology* 3:31. DOI 10.1186/s40462-015-0061-6. [published refereed]

\*Sivle, L, PH Kvadsheim, C Curé, S Isojunno, PJ Wensveen, FPA Lam, F Visser, L Kleivane, PL Tyack, C Harris, PJO Miller (*in press*). Severity of expert-identified behavioral responses of humpback whale, minke whale and northern bottlenose whale to naval sonar. *Aquatic Mammals* [in press, refereed]

\*Harris, C.M., D. Sadykova, S.L. DeRuiter, P.L. Tyack, P.J.O. Miller, P.H. Kvadsheim, F.P.A. Lam, and L. Thomas. (*in press*). Dose response severity functions for acoustic disturbance in cetaceans using recurrent event survival analysis. *Ecosphere* [in press, refereed]

\*Isojunno, S, C. Curé, P. H. Kvadsheim, F. P. A. Lam, P. L. Tyack, P. J. Wensveen, P. J. O. Miller (*in press*). Sperm whales reduce foraging effort during exposure to 1-2 kHz sonar and killer whale sounds. *Ecological Applications*

Samarra, F and Miller PJO (2015). Prey-induced behavioural plasticity of herring-eating killer whales. *Marine Biology* 162, 809-821. doi:10.1007/s00227-015-2626-8 [published, refereed]

\* Miller P. J. O., Kvadsheim, P. H., Lam, F. P. A., Tyack, P.L., Curé, C., DeRuiter, S. L., Kleivane, L., Sivle, D. L., van IJsselmuide, S. P., Visser, F., Wensveen, P. J., von Benda-Beckmann, A. M., Martin López, L. M., Narazaki, T., Hooker, S. K. (2015). First indications that northern bottlenose whales are sensitive to behavioural disturbance from anthropogenic noise. *R. Soc. open sci.* 2: 140484. <http://dx.doi.org/10.1098/rsos.140484> [published, refereed]

Curé C, Sivle LD, Visser F, Wensveen P, Isojunno S, Harris C, Kvadsheim PH, Lam FPA, Miller PJO. (2015). Predator sound playbacks reveal strong avoidance responses in a fight strategist baleen whale. *Mar Ecol Prog Ser* 526: 267–282. doi: 10.3354/meps11231 [published, refereed]

\*Wensveen PJ, von Benda-Beckmann AM, Ainslie MA, Lam F-PA, Kvadsheim PH, Tyack PL and Miller PJO (2015). How effectively do horizontal and vertical response strategies of long-finned pilot whales reduce sound exposure from naval sonar? *Mar. Env. Res.* 106: 68-81 [published, refereed]

- Fais, A., Aguilar Soto, N., Johnson, M. Pérez-González, C., Miller, P. J. O., Madsen, P. T. 2015. Sperm whale echolocation behaviour reveals a directed prior—based strategy informed by prey distribution. *Behavioural Ecology and Sociobiology* 69: 663-674. [published, refereed]
- Isojunno, S and Miller PJO (2015). Sperm whale response to tag boat presence: biologically informed hidden state models quantify lost feeding opportunities. *Ecosphere* 6: 1-46 [published, refereed]
- \*Sivle, L.D., Kvadsheim, P.H. and Ainslie, M.A. (2014). Potential for population-level disturbance by active sonar in herring. *ICES J. Mar. Sci.* doi: 10.1093/icesjms/fsu154 [published, refereed]
- Visser F., Miller P.J.O., Antunes R.N., Oudejans M.G., Mackenzie M.L., Aoki K., Lam F.P.A., Kvadsheim P.H., Huisman J. and Tyack P.L. (2014). The social context of individual foraging behaviour in long-finned pilot whales (*Globicephala melas*). *Behaviour* 151: 1453-1477. DOI: 10.1163/1568539X-00003195. [published, refereed]
- \*Antunes R., Kvadsheim P.H., Lam F.P.A., Tyack, P.L., Thomas, L., Wensveen P.J., Miller P. J. O. (2014). High response thresholds for avoidance of sonar by free-ranging long-finned pilot whales (*Globicephala melas*). *Mar. Poll. Bull.* 83: 165-180. DOI: 10.1016/j.marpolbul.2014.03.056 [published, refereed]
- \*Alves, A., Antunes, R., Bird, A., Tyack, P., Miller, P.J.O., Lam, F.P.A. and Kvadsheim, P.H. (2014). Vocal matching of naval sonar signals by long-finned pilot whales (*Globicephala melas*). *Marine Mammal Sci* 30: 1248-1257. DOI: 10.1111/mms.12099. [published, refereed]
- \*Miller, P.J.O., Antunes, R., Wensveen, P., Samarra, F.I.P., Alves, A.C., Tyack, P., Kvadsheim, P. H., Kleivane, L., Lam, F. P., Ainslie, M. and Thomas, L (2014). Dose-response relationships for the onset of avoidance of sonar by free-ranging killer whales. *J. Acoust. Soc Am.* 135, 975-993 [published, refereed]
- \*Fahlman A, Tyack PL, Miller PJ and Kvadsheim PH (2014). How man-made interference might cause gas bubble emboli in deep diving whales? *Frontiers in Physiology* 5: 1-6. [published, refereed]
- \*von Benda-Beckmann, A.M., P.J. Wensveen, P.H. Kvadsheim, F.P.A. Lam, P.J.O. Miller, P.L. Tyack, M.A. Ainslie (2014). Modelling effectiveness of gradual increases in source level to mitigate effects of sonar on marine mammals. *Cons. Biol* 28: 119-128. (DOI: 10.1111/cobi.12162) [published, refereed]
- \*Kuningas S, Kvadsheim PH, Lam FPA, Miller PJO (2013). Killer whale presence in relation to naval sonar activity and prey abundance in northern Norway. *ICES J. Mar. Sci.* (Sept 4. doi:10.1093/icesjms/fst127) [published, refereed]
- Aoki K, Sakai M, Miller PJO, Visser F, Sato K (2013) Body contact and synchronous dives in pilot whales. *Behavioural Processes* 99, 12-20. [published, refereed]
- Oliviera, C., Wahlberg, M., Johnson, M., Miller, P. J. O., Madsen, P. T. (2013). The function of male sperm whale slow clicks in a high latitude habitat: Communication, echolocation or prey debilitation? *J. Acoust. Soc. Am* 133, 3135-3144. [published, refereed]
- Curé, C., Antunes, R., Alves, AC., Visser, F., Kvadsheim, PH., & Miller, PLO (2013). Responses of male sperm whales (*Physeter macrocephalus*) to killer whale sounds: implications for anti-predator strategies. *Scientific Reports* 3 : 1579 (DOI: 10.1038/srep01579) [published, refereed]

- Curé, C., Antunes, R., Samarra, F., Alves, A-C., Visser, F., Kvadsheim, P.H., Miller, P.J.O. (2012). Pilot whales attracted to killer whale sounds: Acoustically-mediated interspecific interactions in cetaceans. *PlosOne* 7:1-5 [published, refereed]
- \*Miller, P.J.O., Kvadsheim, P.H., Lam, F.P.A., Wensveen, P.J., Antunes, R., Alves, A.C., Visser, F., Kleivane, L., Tyack, P.L., Sivle, L.D. (2012). The severity of behavioral changes observed during experimental exposures of killer (*Orcinus orca*), long-finned pilot (*Globicephala melas*), and sperm whales (*Physeter macrocephalus*) to naval sonar. *Aquatic Mammals* 38: 362-401. [published, refereed]
- \*Sivle, L.D., Kvadsheim, P.H., Fahlman, A., Lam, F.P., Tyack, P., and Miller, P. (2012). Changes in dive behavior during sonar exposure in killer whales, pilot whales and sperm whales. *Frontiers in Aquat. Physiol.* 3: article 400 [published, refereed]
- Sayigh, L., Quick, N. Hastie, G. and Tyack, P. (2012) Repeated call types in short-finned pilot whales, *Globicephala macrorhynchus*. *Mar. Mamm. Sci.* 29: 312-324. (DOI: 10.1111/j.1748-7692.2012.00577.x) [published, refereed]
- \*Kvadsheim, P.H., Miller, P.J.O., Tyack, P., Sivle, L.D., Lam, F.P.A., and Fahlman, A. (2012). Estimated tissue and blood N<sub>2</sub> levels and risk of in vivo bubble formation in deep-, intermediate and shallow diving toothed whales during exposure to naval sonar. *Frontiers in Aquat. Physiol.* 3: article 125. [published, refereed]
- \*Sivle, L.D., Kvadsheim, P.H., Ainslie, M.A., Solow, A., Handegard, N.O., Nordlund, N., Lam, F.P.A. (2012). Impact of naval sonar signals on herring (*Clupea harengus*) during summer feeding. *ICES J. Mar. Sci.* (May 14. 2012; doi:10.1093/icesjms/fss080). [published, refereed]
- Shapiro A.D., Tyack P.L., Seneff, S. (2011). Comparing cell-based versus subunit-based methods for categorizing Norwegian killer whale, *Orcinus orca*, vocalizations. *Animal Behaviour* 81: 377-386. [published, refereed]
- von Benda-Beckmann, AM, FPA Lam, DJ Moretti, K Fulkerson, MA Ainslie, SP van IJsselmuide, J Theriault, SP Beerens (2010), Detection of Blainville's beaked whales with towed arrays, *Applied Acoustics* 71, 1027-1035. [published, refereed]
- \*Doksæter L, OR Godø, NO Handegard, P Kvadsheim, FPA Lam, C Donovan and P Miller (2009). Behavioral responses of herring (*Clupea harengus*) to 1-2 kHz sonar signals and killer whale feeding sounds. *J. Acoust. Soc. Am.* 125: 554-564. [published, refereed]